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Optimal sensor placement for multi-setup modal analysis of structures

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ABSTRACT

Modal tests on large structures are often performed in multiple setups for practical reasons. Several sensors are kept fixed as reference sensors over all setups, while the other, so called roving sensors, are moved from one setup to another. This paper develops an optimal sensor placement strategy for multi-setup modal identification, which simultaneously optimizes the locations of the reference sensors and roving sensors. As an optimality criterion, the Information Entropy is adopted, which is a scalar measure of uncertainty in the Bayesian framework. The focus in the application goes to repetitive structures where modes typically occur in clusters, with closely spaced natural frequencies and similar wavelengths. The proposed strategy is illustrated for selecting optimal positions of uni-axial sensors for a repetitive frame structure. The influence of the number of reference sensors and two strategies for positioning roving sensors, i.e. a cluster and a uniform distribution of roving sensors, are investigated. The number of reference sensors is found to be preferably equal to or larger than the number of modes to be identified. In this case, the information content, as quantified by the Information Entropy, is not very sensitive to the roving sensor strategy. If less reference sensors are used, it is highly preferred to distribute the roving sensors uniformly over the structure instead of clustering them. The proposed strategy has been validated by an experimental modal test on a floor of an office building of KU Leuven, which has a nearly repetitive structural layout. The results show how optimally locating sensors allows extracting more information from the data. Though the focus is on applications involving repetitive structures, the proposed strategy can be applied to multi-setup modal identification of any large structure.

1. Introduction

Modal analysis [1,2], i.e. identifying modal characteristics from measured responses, can be used for many purposes, such as model updating, structural health monitoring, damage detection and structural control. The accuracy of the identified modal characteristics depends on the number and locations of sensors. The number of positions covered in the experiments

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should be sufficiently large to accurately represent the mode shapes, i.e., to avoid spatial aliasing. Due to practical limitations on the number of sensors, modal testing of large structures is usually carried out in multiple setups [3]. The number of setups determines the measurement time. It is therefore necessary to find the optimal number and locations of the reference and roving sensors in order to obtain the required information within a reasonable time.

A careful choice of sensor positions is particularly important for repetitive structures, which have regular structural layout, e.g. buildings with repetitive floor plan. In such structures, modes with clustered natural frequencies occur [4]. It is important to determine proper sensor locations such that the closely spaced modes are distinguished in modal identification. The distinction of modes is necessary, for example, in model calibration when pairing the identified and computed modes.

The dynamic behaviour of repetitive (periodic) structures has been investigated by means of wave propagation analysis [5,6] based on the Floquet theory. Characteristic free waves and propagation constants are used to describe the dynamic behaviour of infinite periodic structures [7]. For a one-dimensional infinite periodic structure, n_c pairs of free waves can propagate through the structure at any frequency with n_c the number of coupling degrees of freedom (DOFs) between two adjacent units. Each pair contains identical but opposite going free waves, characterized by a negative and positive pair of propagation constants. The real part of the propagation constant represents the attenuation of the wave across the unit cell and the imaginary part represents the corresponding phase change.

The natural frequencies of finite periodic structures have been studied based on the wave propagation analysis for both mono-coupled [8] and multi-coupled [9] one dimensional periodic structures. For mono-coupled structures, the adjacent units of a periodic structure are coupled by a single DOF; while in a multi-coupled structure, the units are connected by multiple DOFs. In [8], the natural frequencies of finite periodically supported beams, representing mono-coupled one-dimensional periodic structures with symmetric units, were studied by analyzing the propagation constants. Both simply supported and clamped ends were considered as the boundary conditions of the beams. It was found that the natural frequencies lie inside or at the boundaries of the propagation zones of the structure and the number of modes in each propagation zone is equal to the number of bays [8]. A propagation zone is a frequency range where the free characteristic wave is not decaying, i.e. the real part of the propagation constant is zero. It can therefore be concluded from the study in [8] that mode clustering occurs in the propagation zone of mono-coupled periodic structures with symmetric units and free or clamped boundaries. For multi-coupled periodic structures, the analysis becomes more involved as there is more than one pair of free waves at each frequency. In a frequency range where there is only a single pair of non-decaying waves, the number of modes is less than or equal to the number of bays if the periodic structure has a sufficiently large number of units [9]. The number of modes outside of these frequency ranges is difficult to predict on beforehand.

In order to distinguish between clustered modes in the modal identification of repetitive structures, a careful choice of sensor locations is needed. Optimal sensor placement has received considerable attention in the field of structural dynamics [10–19]. Criteria proposed for optimal sensor placement include the Modal Kinetic Energy [11,12], Effective Independence [11], some norm (e.g. determinant and trace) of the Fisher Information Matrix [13,14], Information Entropy (IE) [15] and the off-diagonal terms of the Modal Assurance Criterion (MAC) matrix [16]. Modal Kinetic Energy [11,12] is used to select the sensor locations with possibly the largest modal responses. Effective Independence [11] aims at selecting the sensor locations such that the observed modes are linearly independent. It was found that the Effective Independence method is an iterated version of the Modal Kinetic Energy method [17]. The Effective Independence method is intrinsically equivalent to maximizing the determinant of the Fisher Information Matrix. The Fisher Information Matrix [13,14] is the inverse of the covariance matrix of the estimates characterizing the uncertainty on the estimated parameters, which can be modal coordinates for modal identification or parameters related to the stiffness, mass and damping of the structure for parameter estimation. When the sensor locations are chosen to maximize some norm (determinant, trace) of the Fisher Information Matrix, the estimation uncertainty is minimized. In the Bayesian framework for parameter estimation, Papadimitriou, Beck and Au [15] have proposed to minimize the Information Entropy. The Information Entropy is defined as a scalar measure of the uncertainty in the parameter estimates. If the number of data is sufficiently large, minimizing the Information Entropy becomes equivalent to maximizing the determinant of the Fisher Information Matrix [18]. The influence of the spatial correlation of the prediction errors on the Information Entropy [19] was studied. It was found that this avoids closely spaced sensors which are generally believed to provide redundant information. The Modal Assurance Criterion (MAC) is a measure of the collinearity between two mode shape vectors [1,20]. Minimizing the off-diagonal terms of the MAC matrix results in less dependent mode shape vectors. The Modal Kinetic Energy method, Effective Independence method and the MAC matrix method can be used to determine the optimal sensor locations for modal identification of structures. The Fisher Information Matrix method and Information Entropy method are suitable for both modal identification and parameter estimation, depending on the type of the estimation parameters.

Finding the optimal sensor locations by full enumeration of all sensor configuration candidates is difficult or even impossible when the number of possible sensor locations is large. A number of studies have focused on computational algorithms which can improve the efficiency, including heuristic algorithms [18,21,22], genetic algorithms [23,24] and meta-heuristic algorithms [25]. Genetic algorithms [23,24] have been used to find optimal solutions of sensors locations. Studies on meta-heuristic algorithms inspired from nature were also conducted [25]. As an alternative to these algorithms which involve a random search component, Sequential Sensor Placement algorithms have been studied. Based on the Information Entropy, two heuristic algorithms i.e. Forward and Backward Sequential Sensor Placement (FSSP and BSSP) have been proposed [18] to find suboptimal sensor locations. It was found that these Sequential Sensor Placement algorithms generally